

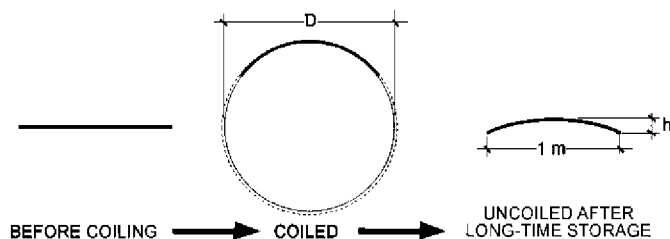
# Influence of coiling on the stress relaxation of prestressing steel wires

*The possible deleterious effects of coiling and long-term storage of coiled wires on the stress relaxation behaviour of prestressing steel wires has been checked by means of experimental work and a simple analytical model. The results show that if the requirements of standards are fulfilled (minimum coiling diameters), these effects can be neglected. However, some other factors, such as previous residual stresses, long-term storage or storage at high temperatures, can trigger or emphasize this damage to the material. In the authors' opinion, checking the final curvature of the wires after uncoiling prior to prestressing, as required in some standards, is to be recommended.*

**Keywords:** prestressing steel, stress relaxation, residual stresses

## 1 Introduction

The coiling process and long-term storage of coiled wires can produce some deleterious effects in the mechanical behaviour of prestressing steel wires. There is also experimental evidence, supported by manufacturers and contractors, that stress relaxation losses increase in coiled wires and strands, particularly after long-term storage, or if coiled with small diameters. This is due to the stress relaxation of the outermost stressed fibres in the wires during storage. Even if plastic deformations are avoided in the coiling operations, as is well known, plastic strains are generated during stress relaxation. After uncoiling, such plastic strains are responsible for a residual curvature (as shown in Fig. 1) and the appearance of residual stresses. When loading the wire, these residual stresses add to the external loads, giving rise to an increase in the stress relaxation losses.



**Fig. 1.** Sketches of wire shapes along coiling and uncoiling and notation used in the text. The sagitta  $h$  is the distance from the midpoint of the wire arch (when uncoiled) to the midpoint of its chord, when the chord is 1 m.

The existence of a residual stress state in the wires prior to the coiling process, due to a poor stress-relieving treatment after cold-drawing, could emphasize these effects.

Furthermore, to avoid or reduce such an occurrence, design codes and standards [1] have set up limits for the inner diameters of drums on which wires and cables are coiled during transport and storage. Such limits are intended to avoid plastic strains in the outermost fibres. In addition, some codes suggest checking the final curvature before prestressing, measuring the maximum values for sagitta  $h$  over 1 m of uncoiled wire or strand (see Fig. 1):  $h = 25$  mm for wires and 20 mm for strands [2]. Even so, if enough time is allowed to expire, plastic strains can develop due to stress relaxation.

The purpose of this paper is to study how certain parameters, such as drum diameter or storage time, influence relaxation losses. This study has been carried out through a series of experiments on wires coiled on drums with different diameters. In order to provide a reasonable explanation and to quantify the influence of the various factors, a simple model is developed. The model gives relaxation predictions in good agreement with the experimental results, and provides recommendations for manufacturers and designers.

## 2 Experimental programme

### 2.1 Mechanical properties of wires

For this research, wires were manufactured by cold-drawing eutectoid steel rods of 12 mm diameter by means of a commercial procedure. After six drawing passes the final diameter was 7.0 mm. This procedure generates residual stresses with tensile stresses on the surface [3]. To reduce these residual stresses to some extent, a thermomechanical treatment, known as stabilizing, was applied [4].

Standard tensile tests were performed according to ISO 15630-3 [5]; the results are given in Table 1. Moreover, stress relaxation tests at different initial loads, ac-

**Table 1.** Tensile properties of 7 mm diameter steel wires

$\sigma_{0.1}$ (MPa)	$\sigma_{0.2}$ (MPa)	$\sigma_{uts}$ (MPa)	$\epsilon_m$ (%)
1679	1704	1823	5.79

**Table 2.** Relaxation losses at 120 hours (measured and predicted) after uncoiling; also, data of average tensile surface residual stresses after uncoiling and sagitta

Uncoiled diameter (mm)	Measured relaxation losses		Predicted relaxation losses		Residual stresses* (MPa)	h (mm)
	(%) 70 % uts	(%) 80 % uts	(%) 70 % uts	(%) 80 % uts		
initial straight	1.8	3.7	–	–	–	0
9000	1.9	4.6	2.3	4.4	80	28
1000	4.0	6.7	4.2	6.7	100	500
500	5.5	6.4	5.9	7.8	120	–

\* Average surface residual stresses.

cording to ASTM E328 [6], as well as measurements of residual stresses on the ferrite phase across the wire section [3, 7] were performed. These results are summarized in Figs. 2 and 3.

## 2.2 Coiling and uncoiling of wires

As already mentioned, some standards propose a minimum diameter for the drum on which wires are to be coiled, usually 225 times the wire diameter [1, 2]. To test the influence of drum diameters, two batches of wires were coiled at smaller diameters than those recommended by the standards, and another at the minimum drum diameter according to the standards. All three batches remained coiled for 120 hours.

After uncoiling, the wires were no longer straight and displayed curvatures that could be fitted around circles of 500, 1000 and 9000 mm diameter. The last one almost satisfied the standard [2], with  $h = 28$  mm. Surface residual stresses on the ferrite phase were also recorded.

## 2.3 Stress relaxation tests

In order to investigate how residual stresses due to coiling influence the stress relaxation behaviour of steel wires, stress relaxation tests were performed at different initial loads – 70 and 80 % of the ultimate tensile stress (uts) – at room temperature and for up to 120 hours.

The test results are shown in Table 2. Each figure is an average value of three tests (the maximum difference

was less than 0.2 %). The average tensile surface residual stress recorded in all batches, straight as well as coiled, also appears in this table in order to highlight its role in stress relaxation. Residual stresses were computed from measurements on the ferrite phase, as remarked in [8].

## 3 Discussion of experimental results

The purpose of this section is to provide a simple model that is able both to explain the experimental results and to predict the influence of coiling diameter and storage time on the stress relaxation of steel wires.

### 3.1 An analytical model to study the influence of coiling

An analytical model has been used to reproduce the evolution of the stress profile on the cross-section of the wire during the coiling-storing-uncoiling process and to predict the influence of this procedure on the relaxation test.

The model is based on *Navier's* hypothesis ('plane sections before loading remain plane after loading') and the input data are the stress-strain curve of the material and the relaxation losses curve for different initial loadings (Fig. 2).

The main characteristics of the model can be summarized as follows:

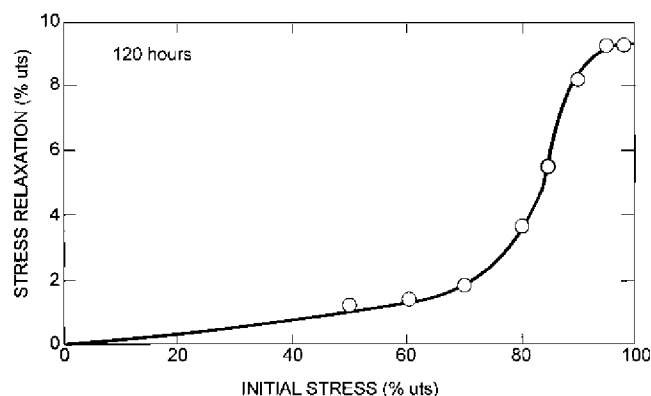
- The cross-section is divided into a bunch of fibres.
- The stress profile is obtained with a simple cross-sectional calculation based, as already mentioned, on *Navier's* hypothesis.
- The initial residual stresses profile is obtained considering an average value for every fibre, but different between two fibres. These average values are obtained from the residual stresses profiles shown in Fig. 3.

Each step is summarized below:

#### 3.1.1 The effect of the coiling-storing-uncoiling process on the wire cross-sectional stress profile

Fig. 4 shows the evolution of the wire cross-sectional stress profile during a coiling-storing-uncoiling process.

- Profile 0. Initial state: No stresses.
- Profile 1. After coiling, due to a bending moment: Note that in this example stresses remain below the yield stress.
- Profile 2. After some time in the coil: Tensile stresses relax, even in the elastic regime, according to Fig. 2, which



**Fig. 2.** Stress relaxation losses at 20 °C after 120 hours for different initial loads

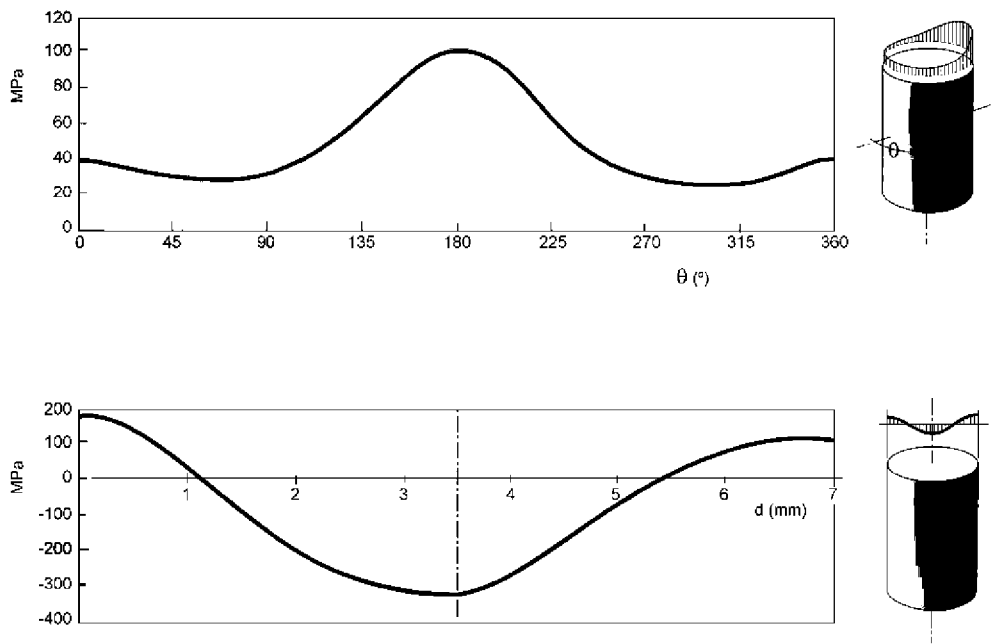


Fig. 3. Residual stresses: (top) surface tensile residual stresses; (bottom) residual stresses across the diameter

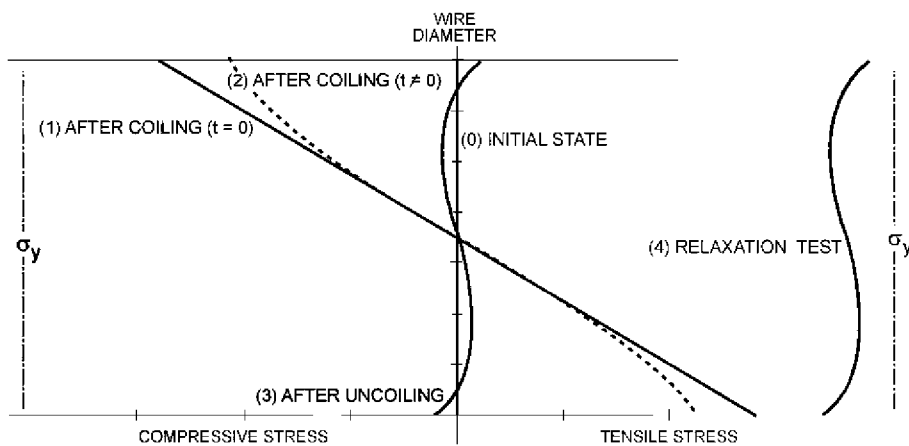


Fig. 4. Stress profiles during coiling, storage, uncoiling and initial relaxation test for wire without initial residual stresses

leads to the stress losses being inhomogeneous across the section of the wire, i.e. higher in the outer fibres.

- Profile 3. After uncoiling: The stress profile is obtained by subtracting the aforementioned external moment to balance the actual loads. Note that some stresses remain, although the whole stress profile is self-balanced. This is because the stress relaxation occurs in an inhomogeneous form throughout the cross-section. Although the wire had no initial residual stresses before coiling, the coiling-uncoiling operation could generate a residual stress profile.

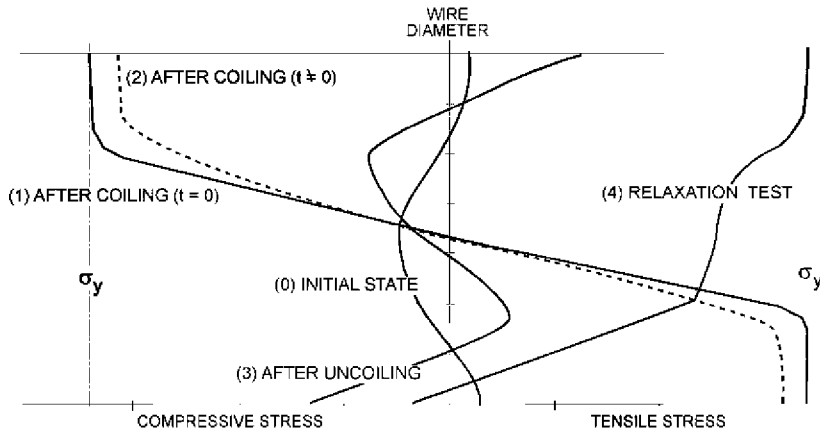
### 3.1.2 Relaxation test

- Profile 4. At the beginning of the relaxation test (at 0.70 uts in this example). Due to the coiling-uncoiling operation, the stress distribution across the section at the beginning of the relaxation test is by no means uniform (be-

cause unloaded wires already have a highly non-uniform stress profile, also shown in Fig. 4). The stress relaxation losses of the wire are the sum of the losses produced throughout the whole section. Note that some fibres are loaded higher than 0.70 uts and therefore higher stress losses should be expected. Further, some fibres are loaded less than 0.70 uts but, as shown in Fig. 2, increases are more critical than decreases. The overall behaviour is that after coiling-uncoiling, wires exhibit relaxation losses higher than those of the wire before coiling.

### 3.1.3 The effect of the residual stresses

If the stabilizing treatment has not been good enough, the wire may have an initial residual stresses profile before coiling. In the presence of *initial residual stresses*, a similar sequence of stress profiles is shown in Fig. 5. Since they are added to the coiling stresses, previous residual



**Fig. 5.** Stress profiles during coiling, storage, uncoiling and initial relaxation test for wire with initial residual stresses

stresses can emphasize the effects of coiling and in some cases could even produce the plastification of external fibres, as shown in the figure.

### 3.1.4 The effect of temperature

Temperature has an influence on stress relaxation; an increment of temperature produces an increase in stress relaxation losses. *Rostásy* [9, 10] has shown that even temperatures of about 40 °C can increase stress relaxation values significantly (some manufacturers have observed values of 1.5–2.0 times the initial values at room temperature). Clearly, storage temperature is a fact to be considered when assessing the influence of storage time on the final properties of the wires.

In order to take into account the effect of higher temperatures, the stress relaxation values of Fig. 2, obtained at room temperature, have been multiplied by a correction factor, according to references [9, 10].

## 3.2 Comparison with experimental results

The model was used to reproduce the effects of coiling on the stress relaxation behaviour of the wires described in section 2. Input data to perform computations were the stress-strain curve of the steel wire and the relaxation curve for different initial stresses recorded at 120 hours and 20 °C, as shown in Fig. 2.

The predicted relaxation values are shown in Table 2 and compared with the measured ones. The agreement is satisfactory, considering the simplicity of the model. Results are particularly good when more realistic conditions are considered, as for uncoiled final diameters of 9000 and 1000 mm. The first one corresponds to a drum diameter of 1500 mm, in accordance with recommendations, i.e. 225 times the wire diameter.

## 4 Final comments

Experiments have shown that coiling operations can increase the stress relaxation behaviour of prestressing wires. It has also been shown that a very simple model is able to capture the main aspects of this phenomenon, i.e. the influence of coiling diameter, storage time and the presence of initial residual stresses. This model can be

easily implemented and improved if more accuracy is needed.

The basic ingredients required for computing are: the stress-strain curve of the wire and stress relaxation data at different initial stresses (preferably at 0.70, 0.80 and 0.90 times the ultimate tensile stress). Knowledge of previous residual stress states would be welcomed because they can modify these effects.

To have a feeling for the evaluation of stress relaxation losses under different circumstances, several scenarios have been considered for a 7 mm wire and a storage time of one year:

- Three coiling diameters: The one recommended by the standards (1.5 m  $\approx$  225  $\times$  0.007), and two smaller diameters of 1.0 and 0.5 m.
- Two storage temperatures: 20 and 40 °C, both of which are reasonable storage conditions. The aim is to check the influence of temperature on the relaxation due to coiling.
- Two times for the relaxation test: 120 hours and one year, after the coil was stored for one year.
- Two residual stress profiles: These are surface tensile stresses, with profiles across the section similar to those shown in Fig. 3; one of 50 MPa, the highest value allowed in some codes [11], and another of 100 MPa, sometimes found in wires for prestressing. A wire with no residual stresses was also included to set a lower level for comparison with previous values.

The stress relaxation losses for these 36 assumptions are summarized in Tables 3 and 4. The relaxation curve after one year, a curve similar to that shown in Fig. 2, was obtained from the experimental values measured at 120 hours, extrapolated to one year according to Model Code recommendations [11].

The relaxation losses at 40 °C have been obtained from the expression provided by *Rostásy* and *Thienel* [9, 10]:

$$R_{iso}(t, \theta) = a(t) \cdot e^{b(t) \cdot \theta}, \text{ in } \%$$

where:

$$a(t) = 0.320 \cdot (1 + 0.23 \ln t)$$

$$b(t) = 0.014 \cdot (1 + 0.03 \ln t)$$

and  $t$  is expressed in hours and  $\theta$  in °C.

**Table 3.** Relaxation losses (%) when loaded at 0.70 uts and 20 °C due to coiling under different assumptions (computed using a simplified model)

Storage temperature = 20 °C									
Drum diameter	$\sigma_R = 0$			$\sigma_R = 50$ MPa			$\sigma_R = 100$ MPa		
	120 h	1 year	h (mm)	120 h	1 year	h (mm)	120 h	1 year	h (mm)
straight	1.8	3.5	0	2.3	4.4	0	3.2	6.2	0
1500 mm	1.9	3.6	6	2.3	4.4	15	3.3	6.3	23
1000 mm	1.9	3.7	9	2.3	4.5	18	3.3	6.3	29
500 mm	3.0	6.0	107	3.2	6.3	115	3.6	6.9	123

$\sigma_R$  is the average surface tensile residual stress, in accordance with Fig. 3a.

**Table 4.** Relaxation losses (%) when loaded at 0.70 uts and 40 °C due to coiling under different assumptions (computed using a simplified model)

Storage temperature = 40 °C									
Drum diameter	$\sigma_R = 0$			$\sigma_R = 50$ MPa			$\sigma_R = 100$ MPa		
	120 h	1 year	h (mm)	120 h	1 year	h (mm)	120 h	1 year	h (mm)
straight	1.8	3.5	0	2.3	4.4	0	3.2	6.3	0
1500 mm	1.9	3.6	6	2.3	4.4	15	3.3	6.3	23
1000 mm	1.9	3.7	9	2.3	4.5	18	3.3	6.3	29
500 mm	3.0	6.4	107	3.4	6.6	115	3.7	7.2	123

$\sigma_R$  is the average surface tensile residual stress, in accordance with Fig. 3a.

This expression gives a relaxation loss of 1.4 times the relaxation at 20 °C.

The following conclusions can be drawn from these results:

Looking at Table 3 it seems that stress relaxation losses do not increase when the recommendations of EN 10138 [1] are fulfilled, i.e. when the minimum internal diameter of the coil is 1.5 m. The EN 10138 recommendation is based on avoiding that any wire fibre carries a load higher than 0.9 times the 0.1 % proof force.

Even with a diameter of 1 m, or in the presence of initial residual stresses (< 100 MPa), the effect of coiling after one year does not appear to have a great influence. Only for very small diameters, such as 0.5 m, does coiling need to be considered.

## 5 Conclusions

1. The experience of manufacturers and contractors, i.e. that coiling at small diameters and over a long period can *increase* stress relaxation losses, is confirmed by the experimental work shown here.
2. Residual stresses due to coiling represent an *additional* source of stress relaxation losses when the wire is loaded.
3. A very simple model is able to predict the evolution of stress relaxation after uncoiling and can be used as a guide when small diameters or high initial residual stresses are considered. The accuracy of the results can be improved by refining the model and the initial data.
4. According to the model used, a storage temperature of 40 °C leads to a small increase in the relaxation losses. This effect is more noticeable for small coiling diame-

ters much lower than the requirements in the standards.

5. The acceptance criterion, based on the sagitta  $h$  [1, 2], is fulfilled in accordance with the predictions of the model (as shown in Table 3) when the coil diameter complies with the recommendations in the standards. Only for a very small diameter, 0.5 m in this example, is  $h$  much greater than 25 mm.
6. This study has confirmed the influence of coiling in the stress relaxation losses [12], though it is also likely to affect other factors, such as fatigue, stress corrosion and tensile strength, when residual stresses are present [13].
7. The results of this work show that if the requirements of standards are met (minimum coiling diameters), the deleterious effects of coiling can be neglected. However, certain other factors such as previous residual stresses, long-term storage, or storage at temperatures higher than room temperature which are difficult to control, can trigger or emphasize this damage. A visual check for identifying the problem with hindsight is to measure the sagitta after uncoiling. In the authors' opinion, measurement of this curvature prior to the final prestressing operations, in accordance with the requirements of pertinent standards, is to be recommended.

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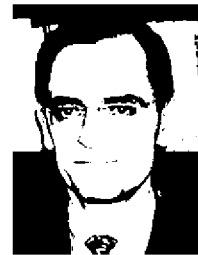


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